

Dynamics of Starclusters and the Milky Way
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Young Stellar Groups, Runaway Stars, and Pulsars

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Abstract. Milli-arcsecond astrometry provided by Hipparcos and by radio observations makes it possible to retrace the orbits of nearby runaway stars and pulsars with sufficient accuracy to identify their parent stellar cluster or association. For two cases it is even possible to deduce the specific formation scenario. The runaway star ζ Oph and PSR J1932+1059 are the result of a supernova explosion which took place 1 Myr ago in a massive binary in the Upper Scorpius association. The pulsar received a kick velocity of about 350 km s^{-1} in this event. The runaway stars μ Col and AE Aur and the isolated eccentric massive binary ι Ori result from a binary-binary encounter, most likely inside the Trapezium cluster, 2.5 Myr ago. Future astrometric missions such as DIVA, FAME and in particular GAIA will allow extension of these studies to a significant fraction of the Galactic disk, and will provide new constraints on the formation and evolution of massive stars.

1. Introduction

Most O and B stars in the Galactic disk are found in young star clusters or OB associations, where they often reside in binaries. About 30% of the O stars and 5–10% of the B stars are found in the field. These objects almost invariably have large space velocities ($30\text{--}200 \text{ km s}^{-1}$). Most of these ‘runaway’ stars appear to be single. Many have high He abundance, and rotate fast.

Two scenarios for the formation of runaway stars are considered viable: (i) a supernova explosion in a massive binary (Zwicky 1957; Blaauw 1961), in which the primary becomes a compact object, and the secondary moves away with a velocity comparable to its pre-explosion orbital velocity, and (ii) dynamical ejection from a dense stellar cluster (Poveda et al. 1967; Gies & Bolton 1986). Both scenarios can explain the properties of the ensemble of runaway stars observed to date. As a result, the relative importance of the two scenarios has been debated extensively in the past decades.

In order to find specific rather than statistical evidence for either scenario, we need to establish a common origin for either a runaway star and a pulsar or a runaway star and a dense stellar cluster. The availability of Hipparcos milli-arcsec (mas) global astrometry for the nearby stars, and of pulsar astrometry provided by VLBI and timing measurements, therefore stimulated us to carry out a systematic study of the past orbits of the nearby runaways and pulsars. The full study will be reported elsewhere (Hoogerwerf et al. 2000); here we restrict ourselves to a brief summary of some of the main results.

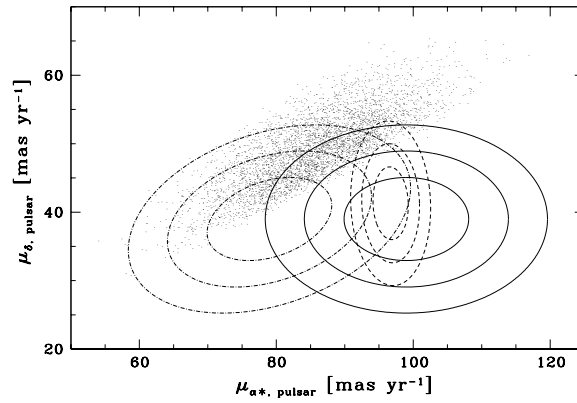


Figure 1. Measurements of the proper motion of PSR J1932+1059. Dot-dash curves: Lyne, Anderson & Salter (1982), solid curves: Taylor, Manchester & Lyne (1993), and dashed curves: Campbell (1995). Contours indicate the 1, 2, and 3 σ confidence levels. The small dots are the values consistent with a close encounter between ζ Oph and PSR J1932+1059 about 1 Myr ago.

2. A binary supernova in Upper Scorpius

Blaauw (1952) proposed that the O9.5V runaway star ζ Oph originated in the nearby association Sco OB2. It is a single star, appears to be a blue straggler, and has He abundance $Y \sim 0.40$ and $v_{\text{rot}} \sin i = 348 \text{ km s}^{-1}$. The space motion of ζ Oph is $\sim 40 \text{ km s}^{-1}$ relative to Sco OB2, and the star traversed the 5 Myr old subgroup Upper Scorpius ~ 1 Myr ago. The kinematics of the expanding HI shell which surrounds Upper Scorpius is consistent with a supernova explosion around the same time, and the present-day mass function of the subgroup indicates that about $40 M_{\odot}$ is missing (de Geus 1992). It is therefore natural to speculate that the supernova occurred in a massive binary, and that ζ Oph is the former secondary. Mass transfer during the binary evolution prior to the explosion would then be the cause of the increased He abundance, the large rotation velocity, and the blue straggler nature. Can we find the compact object?

The catalog of pulsars with distances and proper motions maintained by Taylor, Manchester & Lyne (1993) contains seven objects within 1 kpc with measurement accuracy better than 10%. The radial velocities v_{rad} of these pulsars are unknown, so we retraced their paths in the gravitational field of the Galaxy by numerical orbit integration for a range of $\pm 500 \text{ km s}^{-1}$ in v_{rad} . Taking into account the characteristic age $P/2\dot{P}$ of the pulsars leaves only one likely candidate: PSR J1932+1059. If its $v_{\text{rad}} = 200 \pm 50 \text{ km s}^{-1}$, then it passed through Upper Scorpius about 1 Myr ago, on its way towards the Galactic plane (which it recently crossed). If the pulsar did not originate in Upper Scorpius, then it must have been launched from the Galactic plane some ~ 50 Myr ago. This is unlikely given a characteristic age of about 3 Myr.

Having identified the most likely pulsar, we computed the absolute minimum separation D_{min} between the orbits of ζ Oph and PSR J1932+1059, while sampling the error distributions in position and velocity. The main uncertainties are the errors in the parallax of ζ Oph ($\pi = 7.1 \pm 0.7 \text{ mas}$) and the pulsar

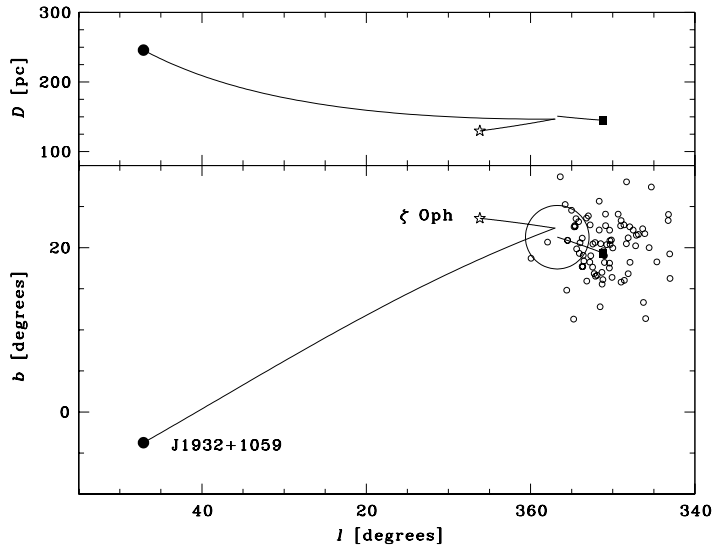


Figure 2. The orbits of ζ Oph, PSR J1932+1059, and Upper Scorpius. The present positions are denoted by a star, a filled circle, and a filled square (center of the subgroup). Top: distance D vs Galactic longitude ℓ . Bottom: orbits projected on the plane of the sky in Galactic coordinates. The present-day positions of the O, B, and A-type members of Upper Scorpius are indicated by the small circles (de Zeeuw et al. 1999). The large circle indicates the position of the subgroup when the supernova explosion created the pulsar and the runaway star.

($\pi = 5 \pm 1.5$ mas, Campbell 1995), and the remaining range in v_{rad} . We found that the distribution of D_{min} is consistent with ζ Oph and the pulsar being *in the same location* 1.0 ± 0.1 Myr ago in Upper Scorpius (Figures 1 & 2). This is compelling dynamical evidence for the binary supernova scenario.

The value of $P/2\dot{P}$ is an uncertain age indicator, and the ~ 3 Myr for PSR J1932+1059 is consistent with the dynamical age of 1 Myr derived here. While the current period is 0.22 seconds, the implied period at birth is 0.18 seconds.

Pulsars are expected to receive a kick velocity \vec{v}_{kick} at birth. Observations of the ensemble of pulsars suggest that \vec{v}_{kick} is a few hundred km s^{-1} (Hartman 1997; Hansen & Phinney 1997). Assuming that ζ Oph and PSR J1932+1059 originated in the same binary allows a determination of \vec{v}_{kick} . Based on the angle between the orbits of the two objects, and the magnitude of the space velocities, we find $|\vec{v}_{\text{kick}}| = 350 \pm 50 \text{ km s}^{-1}$. New VLBI observations of the proper motion and parallax of PSR J1932+1059 which are being obtained by Campbell (priv. comm.) will make it possible to improve this estimate further.

3. A stellar encounter in Orion

Blaauw & Morgan (1954) drew attention to the isolated stars AE Aur (O9.5 V) and μ Col (O9.5V/B0V), which run away in opposite directions from the association Ori OB1 with space velocities of about 100 km s^{-1} each (Figure 3).

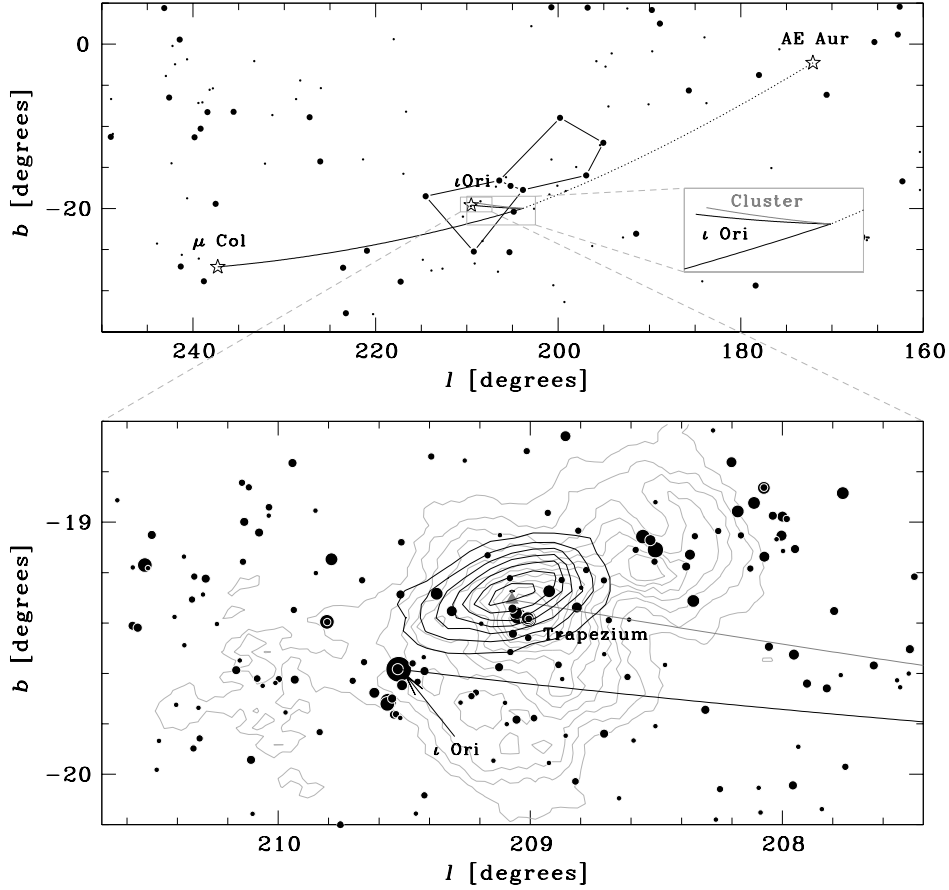


Figure 3. The orbits of μ Col, AE Aur and the binary ι Ori projected on the sky. All three had a simultaneous encounter 2.5 Myr ago. The grey line is the orbit of the parent cluster since the encounter. The large dots denote the stars in the Hipparcos Catalog brighter than $V = 3.5$ mag. The small dots denote the O and B type stars with $3.5 \text{ mag} \leq V \leq 5 \text{ mag}$ (cf. figure 1 of Morgan & Blaauw 1954). The Orion constellation is indicated for reference. Bottom: The predicted position of the parent cluster (solid contours) together with all stars in the Tycho Catalog in the field to $V = 12.4$ mag. The size of the symbols scales with magnitude. The brightest star is ι Ori. The dark and grey lines are the past orbits of ι Ori and the Trapezium, respectively (see top panel). The triangle indicates the predicted present-day position of the parent cluster. The grey contours display the IRAS 100 μ m flux map, and mainly outline the Orion Nebula.

Blaauw & Morgan speculated that both stars originated in the same event in Ori OB1, some 2.5 Myr ago. Gies & Bolton (1986) suggested that this event was an encounter between two hard binaries, which also produced the eccentric massive binary ι Ori (O9III+B1III).

We used the globally accurate Hipparcos proper motions and parallaxes, and published radial velocities to retrace the orbits of ι Ori and the two runaways. We carried out 2.5×10^6 experiments to sample the error distribution in the measurements (the largest uncertainties are in the parallax, as the objects are at distances of $\gtrsim 450$ pc). We found that the distribution of the radius D_{\min} of the minimum volume enclosing the three objects is consistent with AE Aur, μ Col and ι Ori being *simultaneously in one location* 2.5 ± 0.2 Myr ago. This is strong evidence for the dynamical ejection scenario.

It is of interest to ask, where did the binary-binary encounter occur? We assumed that the center-of-mass motion of the four stars involved in the encounter was identical to the mean motion of the parent cluster. By using conservation of linear momentum, we then computed the current location and mean motion of the cluster. This is somewhat sensitive to the masses of AE Aur and μ Col, but all data are consistent with the binary-binary encounter taking place in the nascent Trapezium cluster (Figure 3). This identification is supported by the age of ~ 2 Myr (Palla & Stahler 1999), the high stellar density, the short dynamical time as evidenced by mass segregation (Hillenbrand & Hartmann 1998), and the high binary fraction (Weigelt et al. 1999) of the Trapezium cluster.

4. Conclusions and prospects

The results from the previous two sections demonstrate that runaway stars are created both by binary supernova explosions and by dynamical ejection, and that it is now possible to identify individual events.

Enlarging the sample would provide a probe of the recent history of massive star formation in the Galactic disk, and would constrain the fraction of binaries in young clusters (Portegies Zwart 1999). We therefore took all 3622 O–B5 stars in the Hipparcos Catalog with (i) measured radial velocity v_{rad} (1118), (ii) parallax $\pi > 2\sigma_\pi$ (which translates to a distance less than about 700 pc), (iii) accurate proper motion $\sigma_\mu/\mu < 0.1$, and (iv) space velocity $\vec{v} > 30 \text{ km s}^{-1}$. This produced 56 runaway candidates. Similarly, we took all the pulsars in the Taylor et al. (1993) catalog with (i) measured distance and proper motions (94), a distance estimate of $D < 1$ kpc, and (iii) accurate proper motion $\sigma_\mu/\mu < 0.1$. This leaves only seven pulsars. We then retraced the orbits of all these objects, to identify the sites of origin. This work is in progress.

Both samples are severely incomplete. The Hipparcos Catalog is complete only for $V < 7.3 - 9$ (depending on latitude), and less than a third of the O and B stars in it have a measured radial velocity. Because of beamed radio emission, we cannot observe all pulsars, and not all of those that do radiate in our direction have been found; of these, only a few have an accurately measured proper motion. Even so, to date we have found the parent stellar group for two more pulsars (in addition to PSR J1932+1059) and for ~ 20 runaway stars (10 of which are new). The two pulsars both originate in the ~ 50 Myr old association Per OB3. This is not surprising, as the peak of pulsar production

occurs for the lower-mass B stars, i.e., in old groups. Twenty of the 56 runaway stars can be linked to the nearby associations. Other runaways in the sample presumably originate in open clusters, including a newly-discovered pair of stars running away in opposite directions from the region of the λ Ori cluster. Further progress requires accurate space motions for the young open clusters in the Solar neighbourhood. Some of the remaining runaways (and pulsars) must have originated beyond 700 pc, where our knowledge of the parent groups is poor.

Much can be learned by measuring radial velocities for the nearby O and B field stars, and by increasing the sample of pulsars with measured astrometry. At the current accuracy of about 1 mas in parallax and 1 mas/yr in proper motion, a full census is possible of the nearby 500 pc. Extension to a larger volume requires μ as astrometry, which will be provided by future space observatories such as DIVA, FAME, and GAIA.

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Pavel Kroupa: 1) Dynamical ejection from the Trapezium cluster ≈ 2.5 Myr gives an *important* alternative age estimate that is larger than the typically quoted age. 2) My N-body calculations show that up to 50% of all stars with $M > 8M_{\odot}$ are found at $R > 2R_{\text{tidal}}$ after a few Myr. 3) Ejected low-mass binaries will have highly eccentric orbits. This allows for a test of tidal circularisation theory of fully convective stars.